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SRM Propellant and Polymer Materials Structural Test Program

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INTRODUCTION

The structures and dynamics experimental test program's impetus is to develop the theoretical, analytical, test methodological, and structural characterizational engineering data base for solid rocket motor propellants and polymer materials. All of these areas need basic research and development and must be developed together in a coordinated interrelated manner with proper testing, verification, and correlation. The need for better structural characterization and analysis of the solid propellant grain is dictated by the need to characterize the statics and dynamics of the Space Shuttle Solid Rocket Boosters as a system.

There presently is not a data base of analysis methods and supporting test data which allows an accurate prediction of the propellant or bondline strain or stress for a variety of conditions. A strong emphasis must be placed on structural analysis to support the proposed test program. Each individual test shall have a proper pretest and post test structural analyses which either verifies the structural models or refutes them and points the way for a valid structural model which can be test verified.

SPACE SHUTTLE SRM APPLICATION OF PROPELLANT TEST DATA

Propellant stress relaxation modulus data has been used for propellant structural analysis of the Space Shuttle SRB [1]. The stress relaxation modulus data are obtained by inducing a constant strain or shear in the propellant test specimen and measuring the reaction boundary forces or moments versus time (Fig. 1 and Refs. 1 and 2). The modulus is related to temperature by the introduction of a temperature dependent time shift parameter. Time is simply divided by this factor which has the effect of expanding or compressing the material time scale with respect to the actual time scale of the transient events [1,2,3].

It should be remembered that the stress relaxation modulus is only valid for constant strain while many actual problems do not have a constant strain field and are really transient in nature. It has been proven in test that under transient conditions the modulus is strain rate and static strain dependent [2,4,5]. The documented propellant analyses employed the stress relaxation modulus data in two different analysis methods. One method of application is to assume or select a time during an event such as a long term storage, then the modulus is defined by the stress relaxation data and a linear elastic analysis is completed for that one instant in time [2,6]. The second method of analysis is to use a finite element linear viscoelastic transient computer code [1]. The code used by Reference 1 uses a Prony Series for input data to model the modulus of the assumed linear viscoelastic material with respect to time, as follows:

$$G(t) = G_0 + G_1 e^{-t/\lambda_1} + G_2 e^{-t/\lambda_2} + G_3 e^{-t/\lambda_3} + \ldots$$

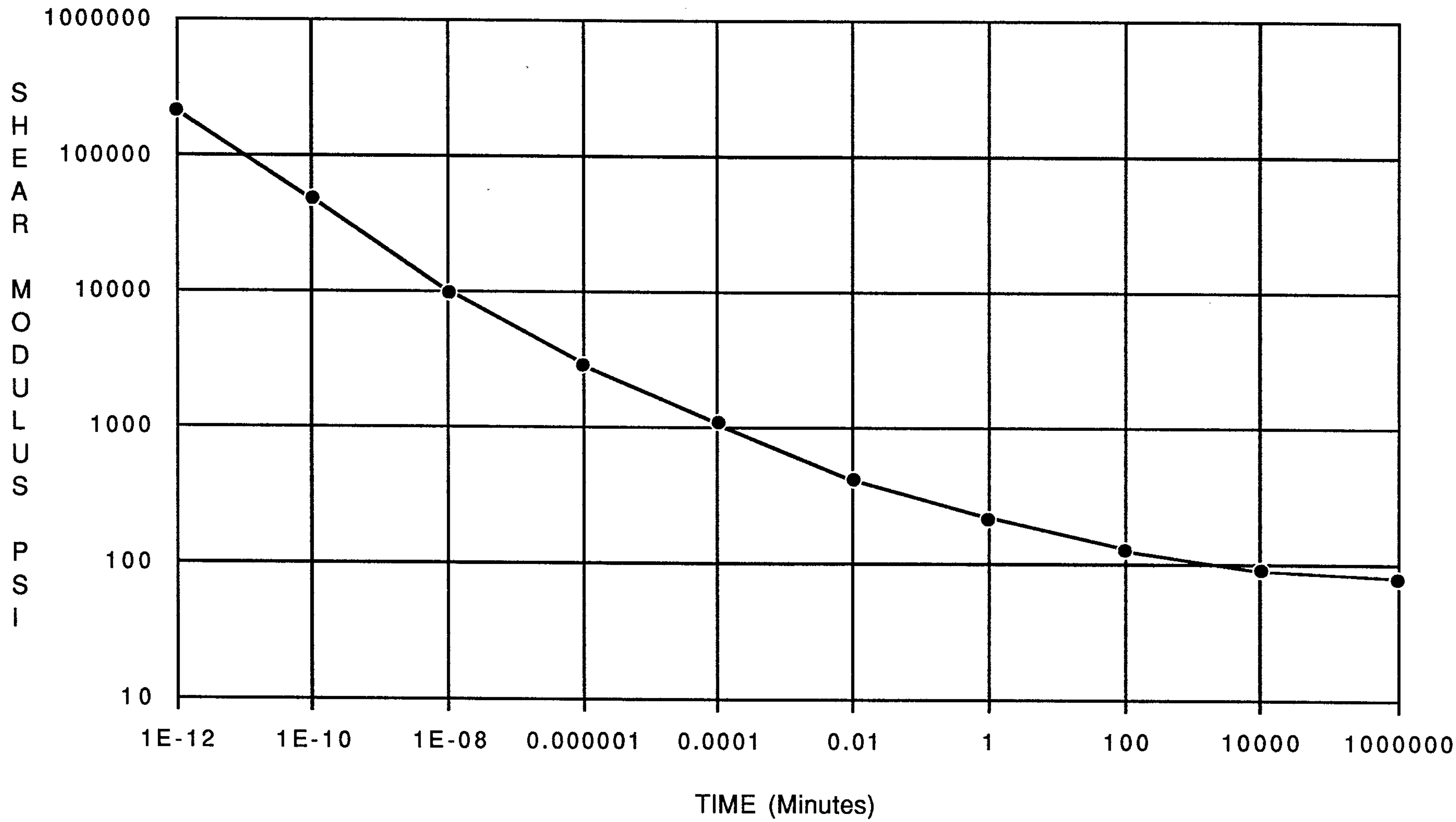

Figure 1. Log shear modulus G(t) versus log time.

The Prony Series material model can be defined conceptually by a very simple schematic consisting of a spring in parallel with a number of Maxwell elements. The Maxwell elements are simply a spring in series with a viscous dash pod damper [3].

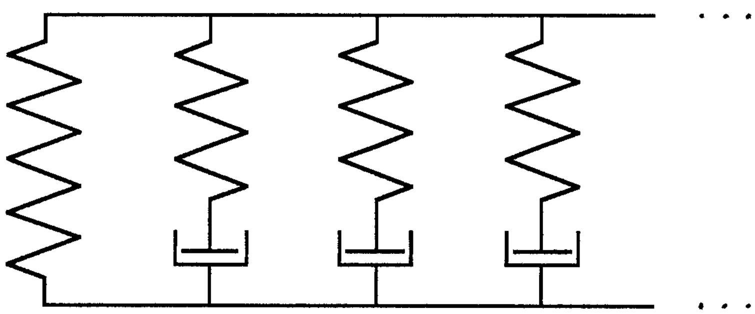

Figure 2. Conceptual schematic of Prony Series material model.

This is the simplest and most numerically convenient viscoelastic model for a material. Figure 3 shows a log log plot of stress relaxation modulus versus time as defined by the Reference 1 fit of the Prony Series equation obtained from Reference 1. Although the function curve goes through the experimental data points, the curve shows an additional oscillation between the data points that was not part of the test data. The series is extremely ill conditioned [7]. A time dependent analysis is then done with this model assuming linear superposition and ignoring a variety of factors which can cause the effective modulus to shift by factors of two and more.

SRM PROPELLANT AND POLYMER MATERIALS TEST PROGRAM NEEDED

The propellants, liners, insulators, inhibitors, bondlines, and seal O-rings of the Space Shuttle SRM's must be experimentally tested to define the dynamic failure criteria and to improve the structural analysis capability with these materials. The present viscoelastic Prony Series model and other analysis techniques are used for the verification of the SRM propellant structural margins. Stress relaxation testing of a coupon of propellant was used to define the Prony Series terms. This model is currently unable to match the test results for dynamic modulus [2]. Proper creep testing has been neglected which could also provide another basic test of the suitability of this viscoelastic model. This viscoelastic model is then used for analysis of the actual SRM with no experimental verification of acceptable basis. The experimental Space Shuttle SRM tests reviewed by the author have been differing from the pretest analysis by factors of 2 to 6 at the test data points. There is no firm basis for accepting currently estimated margins of safety.

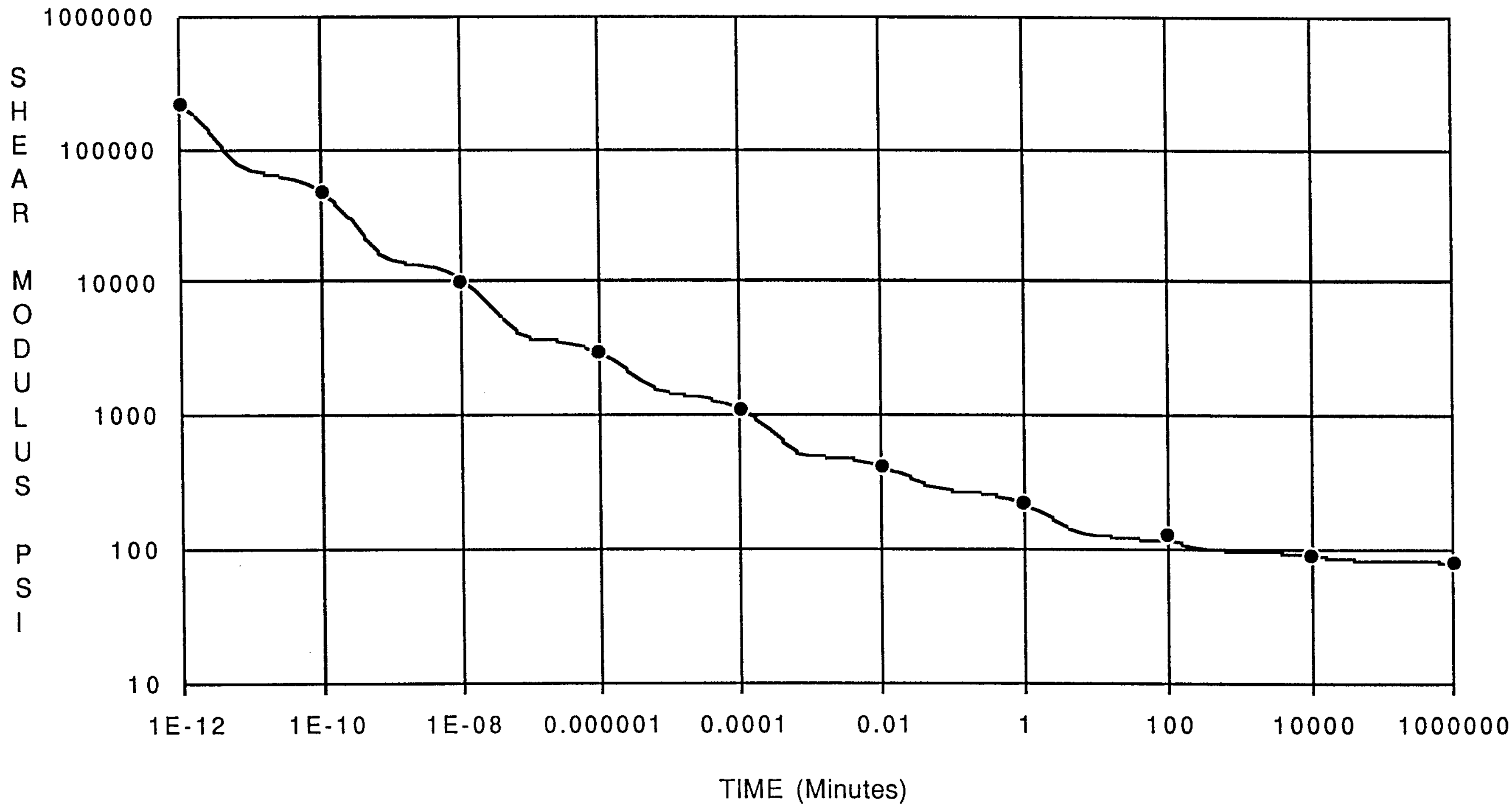

Figure 3. Log shear modulus G(t) versus log time, Prony Series fit.

CURRENT SRM PROPELLANT STRUCTURAL DESIGN ISSUES

The following is a list of reasons why NASA must take advantage of the current knowledge of these materials and structural analysis techniques and computation methods to develop and implement a current and consistent test program for characterizing the materials and developing a unified constitutive theory.

1. SRM margins determination is largely dependent on analysis which cannot be verified by full scale test.

2. The currently used materials model (Prony Series) can not correctly predict results of different boundary conditions of materials coupon testing.

3. The SRM pretest analyses have been off in stiffness by a factor of 2 to 6 from the value necessary to correlate with the experimental test data point.

4. The only proof of the system is the hot firings which do not verify actual margins as being any greater than 1.0.

5. Materials test data indicates that linear superposition does not work for these materials. Thus, all previous analysis is questionable, and an experimental program must find a superposition relation.

6. Testing must establish a dynamic failure criteria. The present failure criteria is static. Past testing on other propellants has shown a significant shift in the fatigue curves with frequency. The static failure value is not the most conservative value for these materials (Fig. 4 from Reference 8).

7. These materials are very temperature dependent and time dependent. Also, the materials have a significant variation in material structural properties from mix to mix (on the order of 50 percent variability). The determination of the margin or safety factor would not be a single number, but a set of time and temperature dependent curves with a mix variation specified in a deviation from these curves.

OBJECTIVES

The SRM propellant, insulation, inhibitor, liners, and seal O-rings have been generally characterized as being made of viscoelastic materials. Although the viscoelastic classification has been generally accepted, close examination of these materials reveal that they are either more complex and nonlinear then classic viscoelastic models or the actual mechanisms should be redefined in a different mathematical form. These material's structural properties exhibit an extreme time dependency. This material time dependency makes it necessary to test characterize the dynamic failure criteria for these materials. Also, this test program has a secondary objective of obtaining a consistent set of materials test data to be used to improve and revise the presently used theoretical material models. The test data will be used to determine the adequacy of the currently used structural math models. Current evaluation of past test data shows drastic inconsistencies (such as dynamic modulus versus stress relaxation modulus) which either mean a combination or any one of three possibilities.

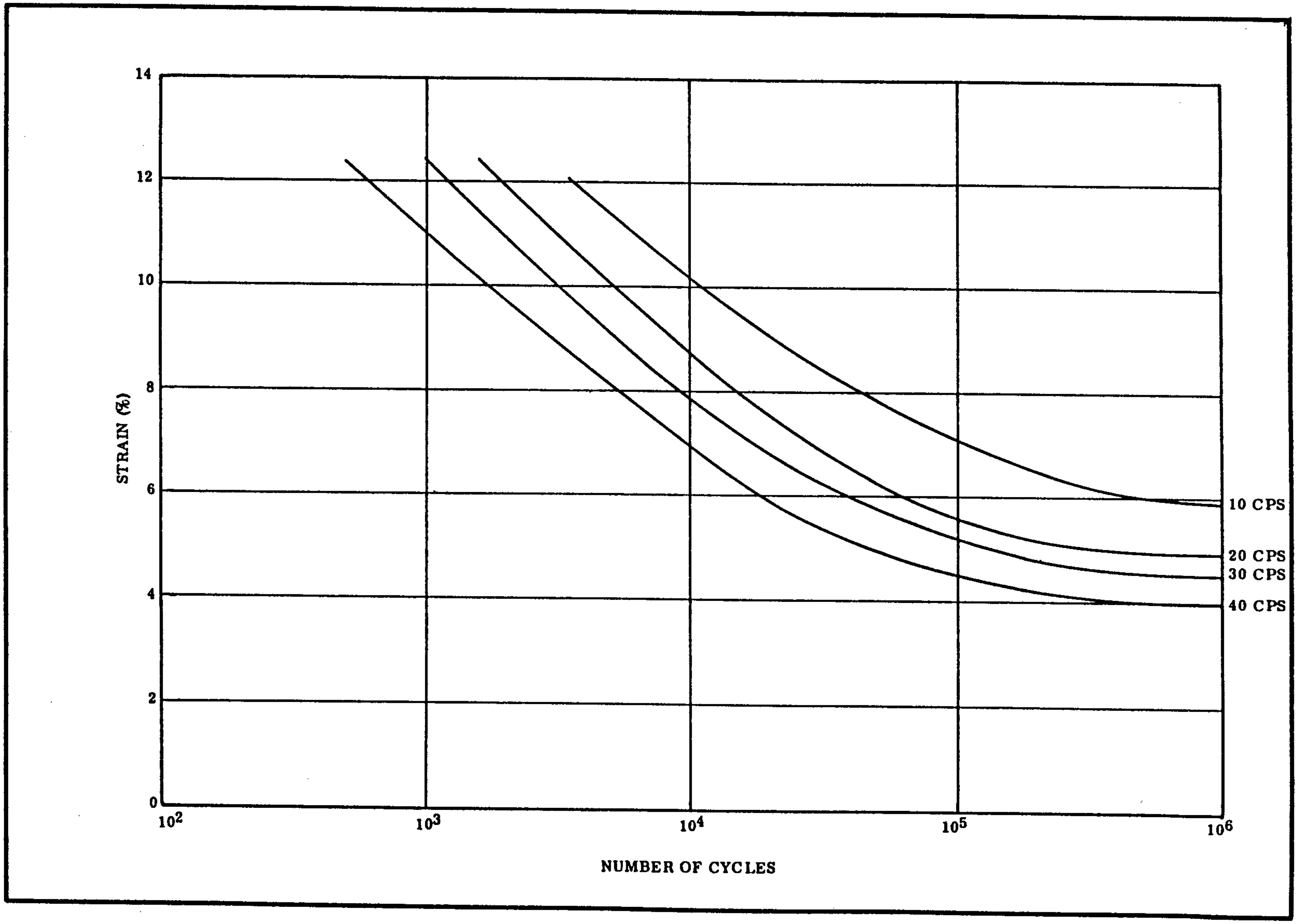

Figure 4. Strain versus number of cycles to failure as affected by frequency.

1. The present viscoelastic models are not correct for a variety of boundary and loading conditions.

2. The basic analysis principle of linear superposition is not valid and a superposition principle must be found.

3. The past testing did not carefully record and correlate known important variables with different tests and with the SRM. (There are also possible unknown factors.)

The above possibilities point out the need for a consistent full set of scientific materials tests with a strong emphasis on structural analysis. These tests must have proper pretest and post test structural analysis which either verifies the structural models or refutes them and points the way for a valid structural model which can be test verified. The testing and the analyses must consider the following known factors and phenomena along with a careful watch and cross checking to discover unknowns.

KNOWN PROPELLANT STRUCTURAL PHENOMANA

1. Time and temperature dependency.

2. Stress relaxation.

3. Strain rate dependency.

4. Static strain dependency.

5. Load and deflection superposition principles.

6. Effects of superimposed pressure.

7. Strain localization, heterogeneity, and anisotropy.

8. Dewetting and dilatation.

9. Hysteresis and stress ratcheting during cyclic loading.

10. Fading memory response.

11. Rapid decrease of stress during unloading.

12. Reverse recovery, healing, and permanent set during rest periods.

13. Compression tension, and biaxial response of particulated composite propellants.

14. Thermal expansion and heat transfer.

15. Static and dynamic failure mechanisms both uniaxial and biaxial.

16. Residual stresses and pressure cure effects.

17. Propellant chemistry, variability, and reproducibility.

18. Aging modification of structural properties.

19. Accumulative damage due to shipping, temperature cycles, and strain cycles.

20. Propellant patches.

21. Stress concentrations (Star patterns, etc.).

22. Humidity effects.

23. Compressible and incompressible behavior.

STATEMENT OF WORK

An investigative consistent test program is needed to characterize the dynamic failure and the time/temperature dependent structural properties of the SRM propellants, insulation, inhibitors, liners, and seal O-rings. A general consistent test program is needed which also characterizes variables such as batch mix, aging, temperature, and percent strain. Additionally, the effects of static and dynamic strain must be characterized along with an experimental verification of load and deflection superposition principles. All of the above must be controlled or at least documented. A strong emphasis must be placed on structural analysis to support these tests. These tests shall have the proper pretest and post test structural analyses which either verifies the structural models or refutes them and points the way for a valid structural model which can be test verified. The following listed tests are extensions of past established test techniques which have been enhanced to investigate uniaxial failure, material modeling, and response. Although these tests are currently deemed complete as the next logical step, there may be a need for the development of additional testing techniques to properly characterize the materials and verify the developed math models.

1. Fatigue Test

Material samples will be fatigue tested providing curves of percent strain versus number of cycles to failure for driving frequencies of 3, 10, 20, 30, 40, and 50 Hz. This testing will also investigate the shift of these fatigue curves with temperature, batch mix, and aging. Also, the test matrix shall check the shift of the fatigue curves due to a superimposed static strain and shear.

2. Bondline Cycle Fatigue Test

Bondline samples of the above materials will be fatigue tested providing curves of load (stress) versus number of cycles to failure for driving frequencies of 3, 10, 20, 30, 40, and 50 Hz. This testing will also investigate the shift of these fatigue curves with temperature, batch mix, and aging. Also, the test matrix shall check the shift of the fatigue curves due to a superimposed static stress and shear.

3. Strain Rate Test

Material samples will be pulled at a constant strain rate to failure. The stress and strain will be documented for the entire event. Investigation will continue with different strain rates at different temperatures.

4. Creep Test

Test material samples are hung in tension with a range of weights, at controlled temperatures. During the course of the test, deflections will be recorded at first in short intervals and then in longer intervals. The sample is then released and the deflections are again recorded over a similar length of time. The creep test shall also be repeated to check the result of load superposition during the creep phenomena. A test matrix of material samples shall be hung in tension with a weight that is increased or decreased at fixed time steps with the previous above procedure for data acquisition. The samples are then released and the deflections are again recorded over a similar length of time.

5. Stress Relaxation Test

Test material samples are subjected to a test matrix of constant percent strain, and stress is recorded with time. The percent strain test matrix shall include a range of strains from 1 percent to the static strain failure point (currently used by SRM manufacturer is 57 percent). The samples are then released and with the free end down the deflections are recorded with time. The stress relaxation test shall also be repeated to check the result of deflection superposition during the stress relaxation phenomena. A test matrix of material samples shall be subjected to strains that are increased or decreased at fixed time steps with the stress and strain recorded with time. The samples are then released and with the free end down the deflections are recorded with time.

6. Dynamic Modulus Test

Dynamic modulis is obtained versus frequency for the materials samples. The dynamic modulus testing shall include both tension and shear testing. The test matrix shall include a series of samples of various sizes. The sample sizes are varied to allow analytical subtraction of test specimen dynamics from actual material frequency dependency. The test matrix shall include control and characterization of strain rate by using driving forces to control deflections, velocities, and accelerations. Also, the dynamic modulus test is repeated for a variety of constant superimposed static strains/shears. The dynamic test machine and fixtures shall be calibrated to characterize the dynamic response for the test machines and sensors.

COMBINING STRUCTURAL TESTING WITH ELECTRON MICROSCOPE IMAGING

The electron microscope has been successfully used to image polymer chains [9,10]. According to Reference 10 transmission electron microscopes and scanning electron microscopes are being utilized in the characterization of polymers. The current success with the electron microscope for the characterization of polymers suggests the possible combination of structural testing with electron microscope imaging of the polymer chains. The development of suitable testing techniques to combine this tool with the experimental structural methods could greatly aid in the theoretical characterization of failure, creep, stress relaxation, aging, curing, crosslinking, temperature effects, time effects, and other phenomena. Also, the electron microscope characterization of the polymer chains of SRM propellant and other polymer materials might be useful as another method for structural quality control.

CONCLUSIONS

A materials test program which builds on and extends past developed testing techniques for SRM propellants has been proposed. This test program will be an important next step in the propellant and polymer materials characterization and development of advanced structural analytical methods. The possible development and integration of electron microscope imaging into the structural testing may lead to a theoretical understanding of polymer materials structural mechanics and failure phenomena. The proposed program is necessary to develop NASA standards for structural material properties, and a test verified math model for these nonlinear materials. The development of these test verified NASA standards and the use of these standards by government and contractor engineering staff will allow a credible and consistent engineering calculation of safety margins.

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16. ABSTRACT

The SRM propellant and polymer materials structural test program has potentially wide application to the testing and structural analysis of polymer materials and other materials generally characterized as being made of viscoelastic materials. The test program will provide a basis for characterization of the dynamic failure criteria for Solid Rocket Motor (SRM) propellant, insulation, inhibitor, and liners. This experimental investigation will also endeavor to obtain a consistent complete set of materials test data. This test data will be used to improve and revise the presently used theoretical math models for SRM propellant, insulation, inhibitor, liners, and seal O-rings.

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